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<p>This project was focused on fundamental issues of modeling and control of flexible structures. Particular problems considered were: patterns of transmission zeroes, sensor placement, robust control, and high-performance control using iterative learning approach. During the grant period a flexible beam control device for experimental purpose was also developed. With most of the work carried out to the extent of laboratory implementation, the following results were concluded:</p> <ul style="list-style-type: none"> (1) For flexible structure control the location of transmission zeroes in the mathematical models critically depend on the location of sensors. For flexible beams the movement of zeroes were mapped out for control design; (2) For flexible structures a class of new compensators called generalized lead/lag compensators were developed. Their implementation is very simple with delay elements. (3) Optimal sensor placement can be based on the robustness of the dynamic observer to parameter uncertainty. A design procedure was developed for this purpose. 			
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AFOSR-TR- 89-1067

FINAL REPORT
TO
AIR FORCE OFFICE OF SCIENTIFIC RESEARCH

Grant Title: Control And Optimization For Observations Of Systems Governed By Controlled
Partial Differential Equations

Grant Number: AFOSR-86-0198

Principal Investigator: Renjeng Su, Department of Electrical and Computer Engineering,
University of Colorado, Boulder, Colorado, 80309

Approved for public release;
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I. Summary

The research under the AFOSR research grant was focused on fundamental issues of modeling and control of flexible structures. Particular problems considered were: patterns of transmission zeroes, sensor placement, robust control, and high-precision control using iterative learning approach. During the grant period a flexible beam control devise for experimental purposes was also developed under a research project funded by the National Science Foundation. With most of the work carried out to the extent of laboratory implementation, the following results were concluded:

- (1) For flexible structure control the location of transmission zeroes in the mathematical models critically depend on the location of the sensors. For flexible beam control it is possible to map out the movement of the transmission zeroes, which is of great importance to the controller design.
- (2) For flexible structures to produce controllers which are robust to modeling errors, a class of new compensators called generalized lead/lag compensators are shown to be very effective. The implementation of the new controller is especially simple using delay elements.
- (3) Optimal sensor placement can be based on the robustness of the dynamic observer to parameter uncertainty. A design procedure was developed for this purpose.
- (4) For high-performance control of flexible structures iterative learning approach is very effective. Further work needs to be done along this line.

In this report we summarize our research findings. We conclude this research by pointing out that iterative learning control method offers a great promise to the difficult problem of controlling flexible structures for high-performance motion.



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II. Task One: Movement of transmission zeroes.

II.1. Statement of work

The objective of this task is to investigate the quantitative relations between the locations of transmission zeroes in the dynamical models of flexible structures and the locations of the sensors. The case of flexible beams is particularly focused.

II.2. Results

In modern approaches to control system design for dynamical systems mathematical modeling is an important first task. The characteristics of the dynamical model usually tell the designer what design methods may be viable and what the limitations are on achievable control performance. One of the most critical characteristics of dynamical models is the location of transmission zeroes. Zero locations of a controlled plant greatly effect the closed-loop stability. In turn they impose critical design limitations. This problem becomes especially pronounced in the case of flexible structures. Due to the nature of low modal damping of flexible structures the transmission zeroes often represent a risk of unstable design to a control designer.

For flexible structures the location of zeroes varies with the location of the sensors. The question of how the zeroes vary specifically with the sensors is therefore of great import to control design. We have considered the case of controlling a Bernoulli beam with one end clamped and the other end free. A position sensor is placed at a location varying from the clamped end to the tip of the beam. A translational or a rotational actuator is placed at the clamped end. With this set-up we have mapped out an interesting pattern of zero movement using the mathematical model of the beam. When the sensor is collocated with the actuator the zeroes and the poles have the usual interlacing property. With the sensor moving away from the actuator toward the tip the zeroes move upward; that is, the frequencies of the zeroes become greater. With the sensor continues to move, the high-frequency zeroes begin to cross the poles, and the interlacing property of the poles and zeroes does not exist any longer. At some sensor location nonminimum zeroes, i.e. zeroes on the right-half plane, occur. With the sensor moving further out to the tip more zeroes become nonminimum phase.

This pattern of zero movement was first observed with mathematical dynamical models. The patterns were later verified with our beam device experimentally.

II.3. Participating Professionals

Principal investigator: Renjeng Su

Co-principal investigator: Hank Hermes

Research assistant: Nassim Arbouz (awarded Ph.D. in 1988), Noureddine Kermiche, and Leo Wang.

II.4. Documentation and Publication

[1] "Robust control of flexible structures" Ph.D. dissertation of Nassim Arbouz, 1988.

[2] Renjeng Su and Nassim Arbouz, "The loci of plant zeroes for flexible beams". This report is now being added with recent experimental results. It will be submitted for journal publication.

III. Task Two: Optimal Sensor Placement

III.1. Statement of Work

The objective of this task is to investigate the problem of optimal sensor placement using the criterion of observer robustness to parameter uncertainty in the dynamical model.

III.2. Results

For completely observable systems the poles of a dynamical observer can be arbitrarily placed. Standard algorithms exist for this pole placement problem. In the case of multiple sensors there exists redundancy which can be used to place the eigenvectors as well as the eigenvalues. It is well known that the closer the eigenvectors are to being orthogonal the more robust the observer is to the parameter uncertainties. It is therefore a usual practice to make the eigenvectors as near being orthogonal as possible.

For mechanical systems which are considered flexible the extent of orthogonality achievable in the observer design depends on the location of the sensors. This is not the case for rigid structures. We explore the idea as a means for determining the optimal placement of sensors in flexible structures. This is the first result using the robustness of observer to study the sensor placement problem, considering the existing approaches to optimal sensor placement are based upon the idea of minimizing the influence of the sensor noise.

III.3. Participating Professionals

Principal Investigator: Renjeng Su

Research Assistant: Nassim Arbouz

III.4. Documentation and Publications

[1] "Robust control of flexible structures" Ph.D. dissertation of Nassim Arbouz, 1988.

[2] Renjeng Su, and Nassim Arbouz, "Robust optimal sensor placement for flexible structures", in preparation.

IV. Task Three: Robust Control Design for Flexible Structures

IV.1. Statement of Work

The objective of this task was to find robust control design methods which produce controllers for flexible structures with good robustness to modeling errors.

IV.2. Results

Neither the classical compensation techniques nor the modern optimal control method is well suited for control design for flexible structures. The former often results in unstable designs. The latter merely gives an iterative mechanism for generating controllers of which the robustness is very difficult to achieve.

In the beginning period of the investigation we applied the robust control design method by Professor Kwakernaak to flexible structure control. In comparison with optimal control designing method we found that the robust control method definitely offered a better approach. As a result of the application of Kwakernaak method a standard pattern of poles and zeroes of controllers was always observed. It primarily consists of a classical lead compensator and a number of complex poles and zeroes which provide the effect of stabilization. Although the controllers are obtained through optimization approach, the effect of stabilization can be explained by the phase argument similar to that used for the classical lead or lag compensation techniques. We call the new family of controllers for flexible structures *the generalized lead and lag compensators*. With these basic compensators the control of flexible structures can be done directly on the complex plane using

root-locus method. Consequently, the robustness of the design is much more attainable than the optimal control design.

IV.3. Participating Professionals

Principal Investigator: Renjeng Su

Research Assistants: Nassim Abouz (Awarded Ph.D. in 1988), Noureddine Kermiche, and Leo Wang.

IV.4. Documents and Publications

- [1] "Robust control of flexible structures" Ph.D. dissertation of Nassim Arbouz, 1988.
- [2] Nassim Arbouz and Renjeng Su, "A generalized lead-lag compensation technique," Proceedings of 26th Annual Allerton Conference on Communication, Control, and Computing, pp. 862-871, 1988.
- [3] Renjeng Su, Noureddine Kermiche, and Leo Wang, "Tip control of a flexible beam with time delays," to be presented to 1989 American Control Conference at Pittsburgh.

V. Task Four: Iterative Learning Control

V.1. Statement of Work

The objective of this task was to develop a new control design paradigm which combines open-loop control and closed-loop control. It was intended to take advantage of repetitive operations and computer memory to increase the power of open-loop control. High-performance control of flexible structures was considered to demonstrate the benefits of the new design paradigm.

V.2. Results

Due to the high-dimensionality of flexible structures it is difficult to achieve high performance in control. We investigated a new control idea of using repetitive operations to better the control performance. Specifically the controller was a combination of an open-loop controller and a closed-loop controller. The system is designed to track a reference signal over a finite time interval. The goal was to perform the tracking repetitively. Essential signals of each iteration were

processed in the open-loop controller to improve the performance of the next iteration.

With this approach the technical problem was to design the combination open-loop and closed-loop controller such that the iterative operations converged to the perfect tracking. The benefits of this new control design method were apparent. First, when the convergence was assured there was no need for high-bandwidth closed-loop design. The high performance was achieved by the idea of repetition and open-loop control. Secondly, after the iteration converges, the open-loop control action became the main portion of the total control action. Thus the system was more robust to sensor failures. Thirdly, it is conceivable that the memory can be built up with open-loop control signals each of which is associated with a tracking reference signal. This memory build-up can be used to define a form of machine intelligence. It provides us a basis for developing supervisory controllers as well.

The learning approach has been applied to the beam control problem. Both the simulation and experimentation showed great promises for further investigation. The results was announced at the 1989 IEEE Workshop on Nonlinear and Adaptive Robotic Control held at Merida, Mexico from May 10 to 12. A full paper is now in preparation for journal publication.

V.3. Participating Professionals

Principal Investigator: Renjeng Su

Research assistants: Noureddine Kermiche (Awarded M.S.

in 1988), and Leo Wang.

V.4. Documents and Publications

[1] "A learning scheme for combination open-loop and closed -loop control systems," M.S. Thesis of Noureddine Kermiche, 1988.

[2] Renjeng Su, Noureddine Kermiche, and Leo Wang, "Flexible beam control by iterative learning," in preparation.

VI. Conclusion

Our investigation in the last two years leads to the conclusion that classical techniques of modeling and control of rigid mechanical structures are not suited for achieving high-performance

control of flexible structures; often they do not even guarantee the basic stability. For flexible structures we must constantly deal with the serious problem of unmodeled resonance modes, some of which may be fairly near the control bandwidth. The control designer is essentially dealing with infinite-dimensional plants. In view of the existing control technologies neither the modeling nor the control issues are satisfactorily resolved from control engineering standpoint. Innovative approaches are still needed.

Based on our research findings we consider the approach of learning control holds a great promise to this difficult control problem. The essence of learning control is to use the memory in control systems and to build up a pool of feedforward control signals and strategies. We feel that in the long run this approach may become an effective way to handle infinite-dimensional and nonlinear systems. Our existing results on learning control has not enabled us to effectively deal with nonminimum-phase plants. It is one of our current focuses to overcome this problem.

On the other hand the learning mechanism that we currently use is but one of many to define learning. Despite our successful results with control of single-input, single-output linear time-invariant systems including flexible beams, we need to broaden our scope of learning mechanisms to cover the case of nondeterministic learning and learning control for nonlinear systems.